

Development and Testing of a Submerged Buoy Wave Power System

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ABSTRACT

A combination of numerical computations, model testing in the controlled environment of a tow tank, and scale prototype testing at sea led to some encouraging findings about a wave energy conversion device coined the “NAF”, but also demonstrated deficiencies in the propeller generator power take-off approach. The experience led to a new approach to power take-off where all the mechanical to electrical power generation equipment are to be housed inside the NAF body and an exterior shape that results in lower drag and less impact ocean sea life.

KEY WORDS

Wave, energy, buoyancy, conversion, ocean

INTRODUCTION

The motion of the water in the waves drives virtually all existing wave energy extraction devices. This presents a challenge because waves moving at relatively slow speeds with very high forces ultimately need to be transformed into fast speeds and low forces in a power generator. As a consequence, most ocean wave energy devices tend to be large and heavy, even for a device producing a relatively small amount of power.

As a solution to this problem, we have been developing a method and device for generating power from ocean waves called the NAF. The key criteria for NAF design are a fully submerged buoy with maximum buoyancy and minimum drag for its’ size and shape, and tendons designed for optimum mooring of the buoy with respect to ocean depth and sea surface. These criteria cause the motion of the NAF to be driven by the fluctuations in the pressure gradients below the sea surface with each passing wave rather than by orbital motion of the water molecules themselves. As such, during each wave passage the NAF is capable of a pendulum-like back and forth motion through the water, actually moving significantly faster than the orbital motion of the surrounding water itself. Such faster motion addresses the wave and velocity contrasts between wave energy resource and energy extraction methodology that is a challenge to all ocean energy devices.

This paper summarizes activity to date and discusses future activity in the NAF development. The combination of numerical computations, model testing in the U.C. Berkeley ship model testing facility, and 5kW prototype testing at sea led to some encouraging findings about the NAF response to real wave conditions, but also demonstrated deficiencies in our original thoughts for a power take-off system for the NAF.

EARLY DEVELOPMENT

Since 2000, AeroVironment Inc. has been leading research and development into the NAF for ocean wave power generation (MacCready, Zambrano and Hibbs, 2003). Devices have been tested in the laboratory and at sea (see Figure 1), and numerical analyses have been refined in its’ response to true wave conditions, particularly for Gulf of Mexico metocean conditions.



Figure 1. NAF Sea Experimentation: Photo of 3m NAF with 5 kW vertical axis-type propeller generator being positioned on its’ mooring prior to being towed and placed in 200 foot deep waters off of Santa Catalina Island, California. (Insert) Undersea photo of 1m NAF with 20 watt Wells turbine-type propeller generators, in the same location

Since energy capture efficiency was the primary focus, an approach for power generation was selected for experimentation. The propeller generator approach was selected since it offered the advantage that propeller-type generators are off-the-shelf technologies. For example, propeller systems have been applied to run-of-the-river, ocean current, and tidal flows (Radkey and Hibbs, 1981). As also mentioned by MacCready, Zambrano and Hibbs (2003), the propeller generator power take-off approach offers a capability for the NAF to extract energy from ocean currents and/or tidal flow as well as wave action.

The combination of numerical computations, model testing in the controlled environment of a tow tank, and scale prototype testing at sea led to some encouraging findings about the NAF response to real wave conditions, but also demonstrated deficiencies in the propeller generator power take-off approach.

For example, numerical analysis and experimental results confirmed the capability of the NAF for amplified motion in surge (Roddier, Cermelli and Zambrano, 2005). During optimum conditions, the NAF horizontal surge to wave height peaked from 8:1 to 10:1. Amplified NAF motion was measured over most of the wave energy spectra.

However, experiments showed that the propeller generator response did not correspond well with the NAF duty cycle, with the propeller spending most of its' time in a non-optimal power conditions, especially as the NAF surge changes direction at the end of its' pendulum-like stroke.

Wells turbines (MacCready and Hibbs, 2001), vertical axis turbines (Hibbs, 2003), and systems with variable blade pitch and blade were analyzed as alternative off-the-shelf propeller-generator designs. Some provided wider efficient response bands, though each added complexity to the power take-off means. In theory, each could be designed to keep up with the NAF motion. However, in practice it appeared all would meet operational issues. Sea testing pointed out these challenges.

Tested at sea were several NAF sizes and mooring configurations (Zambrano, Letourneau and MacCready, 2005), some with relatively simple, though very robust external propellers for power generation. Measured loads on the propeller blades and shafts were very high, even in relatively mild ocean wave conditions, because of the very swift movement of the NAF. There were also difficulties maintaining waterproofing of propeller shaft seals due to these rapid accelerations. Sea trials also identified some other propeller design issues. For example, the rapidly spinning, exposed propellers are an acknowledged hazard to larger marine wildlife that could be attracted to the sound or the motion of the blades.

While most, if not all, of these challenges to using a propeller generator with the NAF are deemed surmountable, a better power take-off solution that minimizes exposure to ocean forces and the surrounding environment while optimally converting the available energy to useful work was sought. This goal has been met with an alternative approach.

IMPROVING THE POWER TAKE OFF APPROACH

The present approach to power take off is an internal power take-off device derived from accelerations of a mass in an inertial reference frame (see Figure 2). In its' simplest form the power take-off system is a bidirectional device inside of which is a large mass, possibly including a flywheel, which rolls on a track and spins an electric generator.

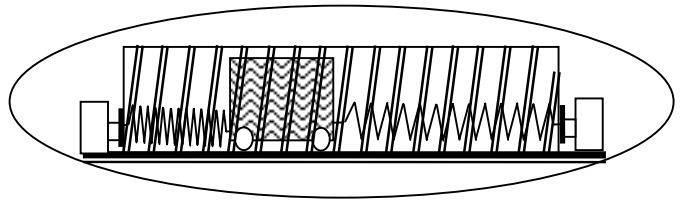


Figure 2. Power Take-Off System The present approach to power take-off for the NAF is an internal device derived from accelerations of a mass in an inertial reference frame. The simple design is a bidirectional device with a large mass, possibly a flywheel, rolling on a track and spinning an electric generator.

This “internal moving mass system” or MMS design should present several solutions to the external propeller constraints while also offering the potential for improved performance and survivability. Such as:

1. Better streamlining for the NAF hull. Any external device attached to the NAF outer surface, or hull, changes the drag and thus slows down the speed at which the apparatus moves through the ocean. The MMS internalizes the power device and eliminates this drag loss issue.
2. Improvement of energy capture efficiency. Energy capture is related to the back and forth motion of the device and the optimum motion occur when the natural frequency of the apparatus is tuned with the frequency of ocean waves. As aforementioned, propeller systems moving back and forth have the problem that they spend most of their time in a non-optimal configuration with respect to the changing wave frequency. While there are propeller systems that can manage this condition, they are complex and require expensive control systems.
3. Better duty cycle. The ocean is rarely still, but there are considerable amounts of time when the waves are small or of long periodicity. However, the NAF moves faster than the wave motion and is responsive to ocean conditions during this time.

4. Helping safeguard the NAF from loss of buoyancy. Any power take-off device that requires parts both outside and inside the NAF hull increases the potential for loss of buoyancy. For example, propellers affixed to the hull of the NAF require rotating shaft seals to transfer the torque to the generator inside the float. Eliminating parts that pierce the NAF hull for the power take-off system are therefore very desirable since buoyancy integrity is so critical to NAF performance.
5. Reduction of damage risk to the tendons that moor the NAF to the sea bottom.
6. Better safety for sea-life. Propeller noise can propagate sound through the water and propellers may get entangled with sea plants and/or ocean debris. Eliminating spinning propellers removes a potentially harmful device to sea life.

MMS RESPONSE ANALYSIS

Analytical and experimental methods were used to investigate the effects of the MMS and determine the coupled response of the NAF to estimate electrical power output. The numerical model used to analyze NAF response to wave motion was modified to include a simplified model of the power conversion mechanism assuming the linear mass-spring-damper system illustrated earlier. The Newton equation of motion for the moving mass was then solved in the surge direction.

Numerical modeling results (see Figure 3) showed the expected decrease in surge amplitude observed around the resonance. Also, the surge motion for the longest periods was slightly increased with the MMS.

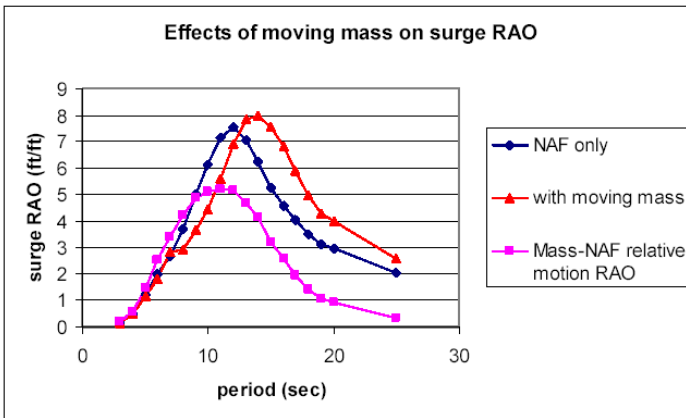


Figure 3. Example of Numerical Modeling Results for NAF only and MMS-NAF Coupled Device

Numerical results were then compared to experiments in the water tank. For the tow tank experiments, the power conversion mechanism was based on a moving mass mechanism sliding inside the NAF. A steel ball, free to roll inside a flooded plastic tube mounted underneath the NAF, modeled it in tank tests. For convenience, the tube was curved around the lower section of the NAF. A decay test was conducted experimentally to determine the equivalent mass, stiffness and damping properties of the ball within the tube. The ball motion stopped after two or three periods, indicating a substantial amount of friction.

The relative motion between the ball and the NAF is a key indicator of the amount of electricity produced by the system. Figure 4 (a and b) show examples of ball surge RAO and the RAO of the relative surge motion between the ball and the NAF. These were obtained via a digital tracking system that recorded NAF and ball motion simultaneously (see Figures 5, 6 and 7). Agreement with the numerical simulations was good for periods smaller than 12 sec. Differences were apparent for larger periods.

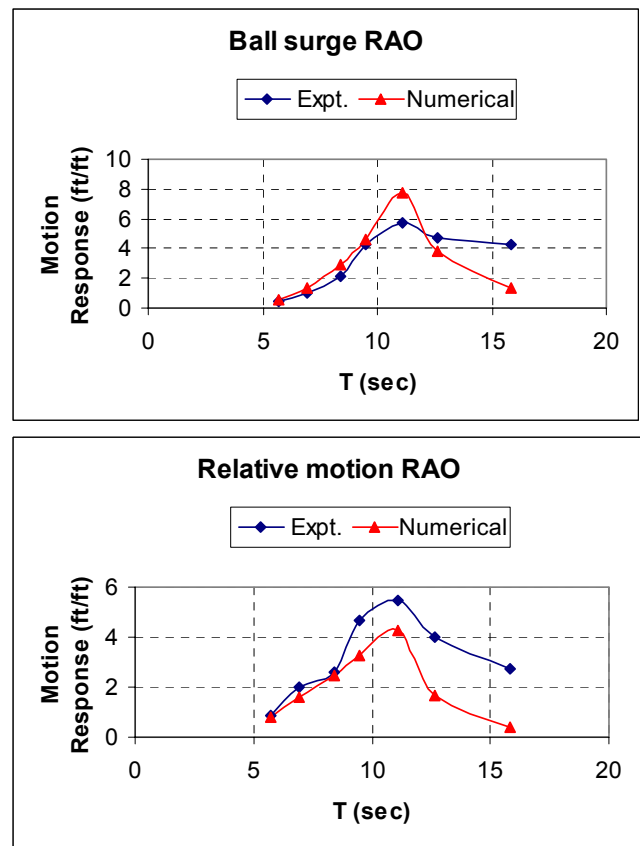


Figure 4. Comparison of a) ball surge and b) relative motion RAO obtained from numerical analysis and digital tracking analysis in tow tank experiments

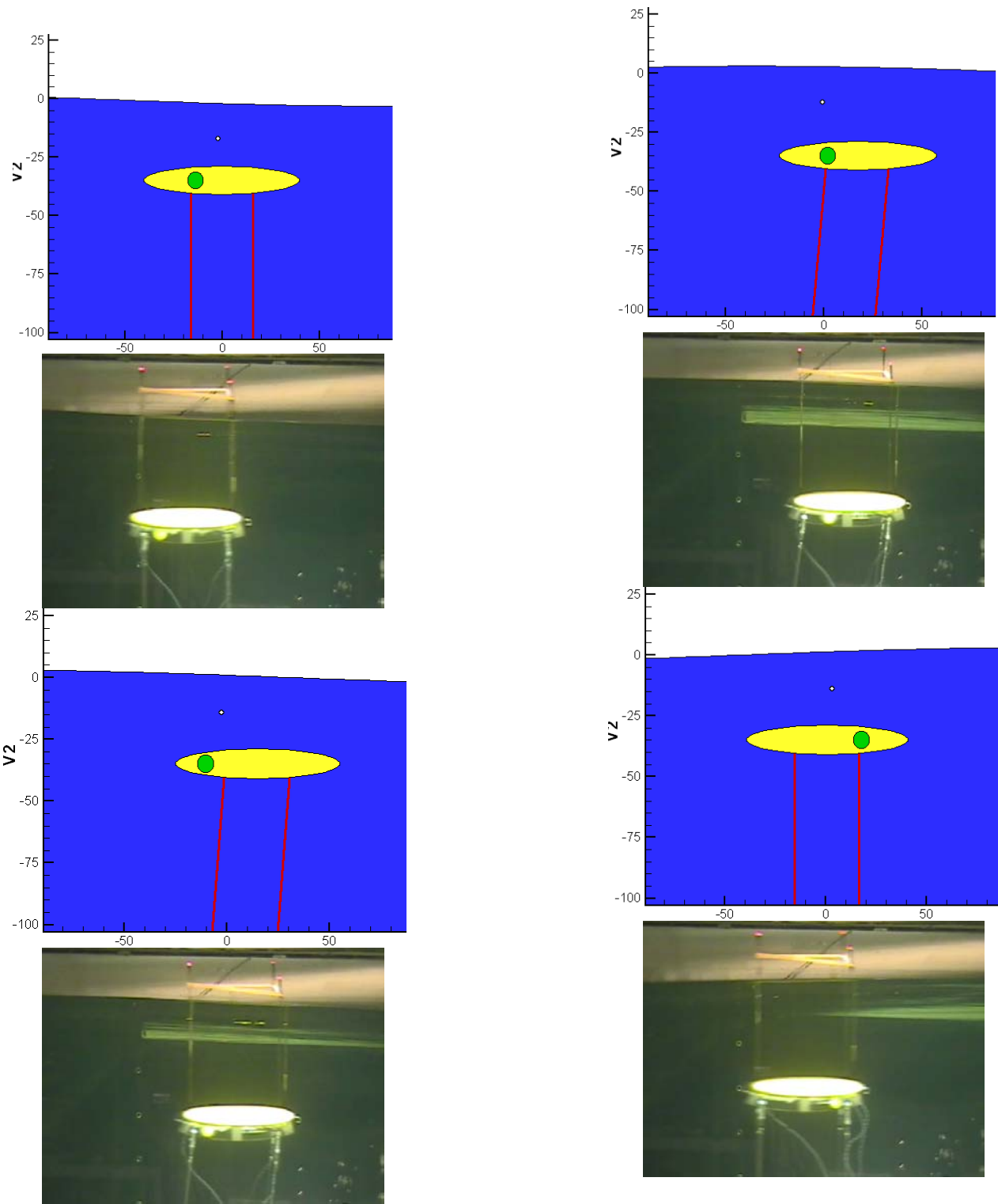


Figure 5. NAF MMS Response Prediction: Shown above is an example sequence of the relative motion between the NAF and the ball corresponding to an 11 sec period. Each step represents a half period of motion starting with the NAF in vertical position and moving toward the right, then reversing direction. Water molecule orbital position is shown by the small white dot in the illustrations.

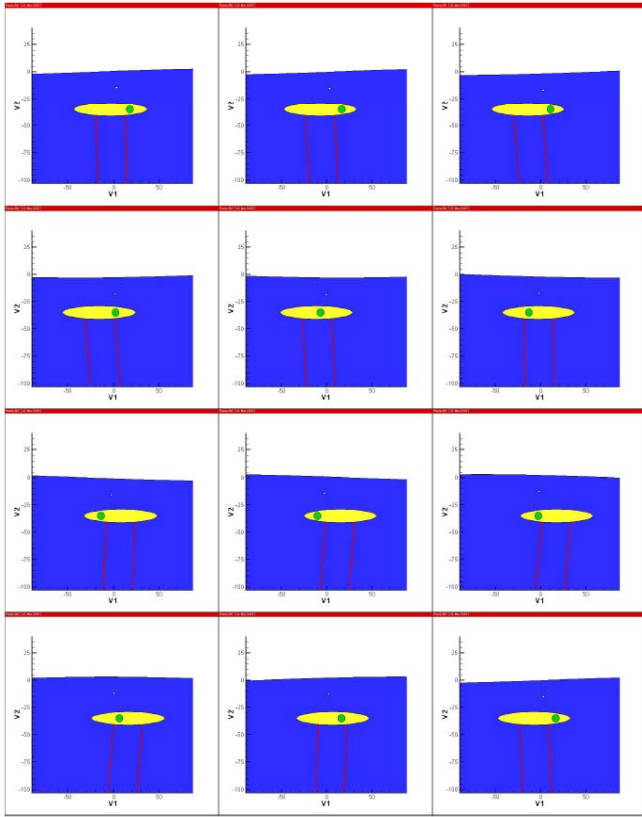


Figure 6. Progression of MMS with Respect to NAF and Wave Motion (wave period 11 seconds.) Snap shots every 30 seconds of wave phase angle are plotted sequentially.

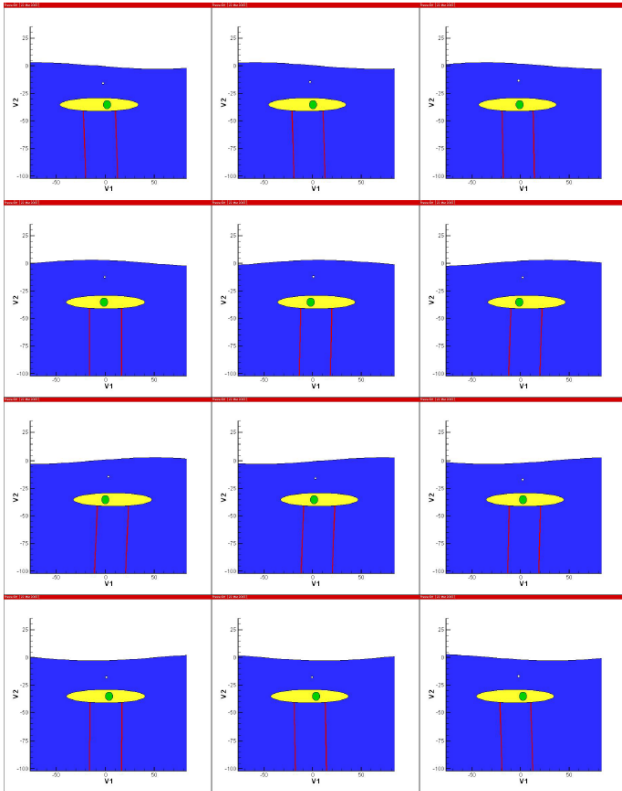


Figure 7. Progression of MMS with Respect to NAF and Wave Motion (wave period 7 seconds) Snap shots every 30 seconds of wave phase angle are plotted sequentially.

CONCLUSIONS

Wave power conversion will not happen overnight, yet it will no doubt occur and will open a new source of power. The NAF is but one example of many ocean energy power systems being contemplated by engineers all over the world. Like many of the systems, anchoring and mooring will be the largest challenge. We, for one, have significant design and analysis work ahead to address this issue. We plan to continue the process of NAF design evolution through the combination of numerical modeling, laboratory testing and sea trials.

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